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Economic optimization from fleets of aero-derivative gas turbines utilising flared associated gas

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ABSTRACT

Associated gas is been wasted to flaring in some parts of the world. The use of these flared gases for both industrial and economic purposes would be very beneficial. This paper presents the development of a model for optimizing the economic return of fleets of gas turbines utilizing flared associated gas. The paper further analyzed the impact of gas turbine degradation on the optimized divestment times of the redundant engines and the economic use of associated gas. Hypothetical but realistic gas turbines were modeled using the Cranfield University performance simulation tool, TURBOMATCH. In furtherance with the investigation, the Techno-Economic and Environmental Risk Assessment (TERA) framework has been adopted for a broad and multi-dimensional optimization of the economic return from the fleets. The results were employed in three degradation scenarios (optimistic, medium, and pessimistic) within the TERA framework to generate economic models. Genetic Algorithm (GA) in MATLAB was used in carrying out optimization to maximize the economic benefit. The result showed that an increase of 1.0% and 1.6% in the energy and net present value (NPV) respectively of the optimized clean fleet as against the baseline were achieved. The economic performance of the fleets shows the optimized fleet (clean) having the highest NPV of $2.84 b and the pessimistic degraded fleet having the least NPV of $2.39 b. More results revealed that degradation reduced the NPV of the project by 4.0%,9.1%, and 15.8% for the three different degradation scenarios. This paper has proposed a model that can be used for the profitable economic utilization of associated gas which would be useful to gas turbine operators and investors.

1. Introduction

There has been flaring of associated gas in some parts of the world. Associated gas is a form of natural gas found in a mixture with crude oil within a reservoir [1, p.1]; [2]. In the process of routine oil and gas exploration activities, natural gas produced in association with oil is burnt in a controlled manner; this process is called associated gas flaring [3, p.ii].

Flaring of associated gas does not only amount to enormous economic waste, but it also leads to life-threatening environmental pollution. High quantity of energy, enormous economic return, and reduced environmental pollution are some of the benefits of using associated gas as fuel for industrial gas turbine engines.

Investors in the economic use of associated gas would want to get the maximum possible economic return at the end of the associated gas utilization project. As such, there is the need for a model for optimizing the financial return of fleets of gas turbines utilizing flared associated gas. This optimization is also necessitated by the fact that there is a continuous gradual decline in the availability of the associated gas over the years of the project. The impact of gas turbine degradation on the economic use of associated gas is considered because over time degradation of engine components takes place due to wear and tear.

The gas turbine engine used for this research is a 43.3 mega watt aero-derivative engine (AD43). It is a simple-cycle, two-shaft, high-performance gas turbine engine whose configuration is similar to that of the General Electric (GE) LM6000 engine.

Ancona et al [4] researched on "optimum sizing of cogeneration plants by means of a genetic algorithm optimization: a case stusy". This study investigated the feasibility of evaluating the optimal plant configuration, energy, and return on investment (ROI) of different scenarios of co-generation plants that utilized natural gas fuel on most occasions. The author estimated the optimal plant configuration for each proposed scenario by using an in-house developed code (Trigen 3). This led to a genetic algorithm optimization to minimize the

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total cost of energy production, this was done with a genetic algorithm-based tool (Energy Grids Optimizer). The author finally carried out an economic analysis to evaluate the profitability of the proposed plant scenario. While the contents and procedure followed by Ancona et al are quite interesting and similar to that of this paper, the effect of plant component degradation was not considered extensively in Ancona et al [4]. Since the project lifespan is 20 years, engine components degradation and, the effect of degradation on the plant configuration, generated energy and on the economic return should have been extensively assessed. In the findings presented by this paper, the effect of the degradation on energy production and on the economic return from the fleet of engines is extensively explored.

Nezhadfard et al [5] researched on 'power generation as a useful option for flare gas recovery: enviro-economic evaluation of different scenarios'. This author considered four power generation scenarios, among which is the gas turbine cycle. Nezhadfard et al [5] lack an in-depth evaluation of gas turbine component degradation and the effect of degradation on the divestment of redundant engines.

Mousavi et al [6] studied 'technical, economic, and environmental assessment of flare gas recovery system: a case study'. The author considered three main scenarios of flare gas recovery to decrease energy consumption and control environmental pollution by using an environmental flow diagram and HYSYS, thermo flow, and aspen software. Among the scenarios considered is the production of power by using a combined heat and power system (CHP) and an internal combustion engine. Findings from the author's research show that flare gas pressurizing and injection to oil wells is one of the best methods to reduce gas flare, it had an internal investment rate of 117% and a payback period of 1.02 years [6]. This author researched on flare gas recovery, his work did not involve the in-depth investigation of the economic implication of using associated gas for power generation using a fleet of degraded gas turbine engines. The effect of degradation on the divestment of redundant engines is also missing in this author's work.

Iora et al [7] investigated 'flare gas reduction through electricity production'; this article investigated the potential energy recovery from a comparatively small flow of associated gas (1150 Nm^3/h). The author's findings show that electricity conversion in the same locality of oil extraction resulted in an economically feasible solution. Due to a lack of data on the operations and maintenance requirements, the author did not consider the operations and maintenance costs associated with her research.

Shayan et al [8] researched on technological and economic analysis of different flare recovery methods. This author also compared different steam and power generation systems. Findings from the author's research show that by employing steam turbine, electricity and heat generation, and combined cycle power plant; electric power generation of the magnitude of 7.323e+5, 4.350e+5, and 1.442e +006 KW respectively were achieved using flare gas as fuel. The rate of investment return for the high-pressure steam generation, steam turbine, electricity and heat cogeneration, and combined cycle are reported to be 18.66, 19.76, 25.79, and 31.97 respectively. Detailed degradation analysis and the effect of the plant's components degradation was not duly considered in this author's analysis.

Zolfaghari et al [9] researched on the recovery of flare gas and its economic utilization. According to the findings of the author, there is a huge energy and economic benefit in the profitable utilization of flare gas. He reported that by employing gas turbines for power generation using the flare gas as fuel, the annual profit achieved was about 480e+006 $. Gas turbine degradation, engine divestment, and their economic implication were not assessed in the author's work.

1.1. Past research on the use of associated gas and their research gaps

Associated gas has been successfully used as fuel for industrial gas turbines to generate power and electricity [10]. The Clark Energy reported in 2013 that about 3.6 million mega watt hour of electricity was generated yearly by the General Electric Jenbacher gas turbine engines [10].

Anosike et. al [11] researched on associated gas utilization using gas turbine engine, the effect of gas turbine degradation on the economic use of associated gas was not considered in this paper. Allison [1] analyzed the influence of degradation on the economic use of associated gas and demonstrated the onset of resource decline and palliative divestment protocol. He recommended that the effect of gas turbine degradation on divestment time should be explored. Allison et. al. [12] also researched the impact of degradation on the economic use of associated gas, however, this research did not take into account the impact of degradation on divestment time for the redundant engines. Obhuo et. al [13] worked on the influence of degradation on the economic use of associated gas. This paper lacked important features like the fleet composition of the baseline fleet, analytical comparison of the baseline and optimized power, analysis of the optimized efficiencies, and the optimized operations and maintenance costs for the project, these elements are vital in research on associated gas utilization.

This paper explored the effect of degradation on the divestment of redundant units of engines in an economic utilization of the associated gas project. As a contribution to knowledge, included in this research are elements missing in Obhuo et. al. [13] such as the design point performance simulation results of the study engine, the fleet composition of the baseline fleet, detailed analytical comparison of the baseline and optimized power, optimized efficiencies, the operations and maintenance costs, and the revenue generated from sold electricity. This paper serves as a guide to investors and governments in the project of associated gas utilization.

1.2. Gas turbine degradation and assumed levels of degradation

Gas turbine engines exhibit the effects of wear and tear after a long time of usage. This associated gas utilization project has a lifespan of 20 years. Considering the effect of engine degradation on the economic return from the fleets is very central for a proper analysis of this research. Degradation in the compressor of the gas turbine is the most common cause of engine degradation [1, p. 21]. As such, this research considered only the degradation (reduction in the pressure ratio, flow capacity, and isentropic efficiency) in the compressor of the gas turbine engine. It was assumed that the degradation was caused by compressor fouling. Different levels of degradation were implemented for the reduction in compressor pressure ratio, isentropic efficiency, and non-dimensional mass flow; this was implemented in the performance simulation model for the degraded fleets. These three parameters were considered because degradation in the compressor affects the compressor pressure ratio, efficiency, and flow capacity [1, p.23]. The influences of the varying rates of degradation on the project were analyzed as represented in Table 1. Optimistic (slow), medium, and pessimistic (fast) degradation are the various rates of degradation considered.

2. Method description

This paper optimizes the economic returns from varying fleets of gas turbine engines for power generation using gas turbines running on associated gas.

2.1. Fuel resources and associated gas availability

Shown in Fig. 1 is the data for the associated gas availability for the paper over an assumed project lifespan of 20 years. Clean natural gas and associated gas were used as fuel for simulating the performance of the same model engines, it was observed that the performance results showed close similarity and there was no significant

Table 1
Rate of Implemented Degradation [13]

Year	Optimistic (%)	Medium (%)	Pessimistic (%)
1	0	0	0
2	1.333	2.666	4.0
3	2.0	4.0	6.0
4	0.667	1.333	2.0
5	1.333	2.666	4.0
6	2.0	4.0	6.0
7	0.667	1.333	2.0
8	1.333	2.666	4.0
9	2.0	4.0	6.0
10	0.667	1.333	2.0
11	1.333	2.666	4.0
12	2.0	4.0	6.0
13	0.667	1.333	2.0
14	1.333	2.666	4.0
15	2.0	4.0	6.0
16	0.667	1.333	2.0
17	1.333	2.666	4.0
18	2.0	4.0	6.0
19	0.667	1.333	2.0
20	1.333	2.666	4.0

difference between the results for both fuels [14, p.60-71]; [11, p.142, 144]; the performance results of the engines in this paper were, therefore, assumed same when using either fuel.

As a result of the need to verify the results obtained from the optimized fleets, there is a baseline analysis for the same results expected from the optimizer, thereby giving room for comparison. The same Techno-Economic and Environmental Risk Assessment approaches were implemented for the baseline and the optimized scenarios. However, the methodology and tools adopted for estimating the fleet composition and best divestment time for the redundant units of engines in the optimized fleets varies from that which was selected for the baseline fleet. The fleet composition and engine units' divestment time for the optimized fleets are given by the optimizer, while that for the baseline fleet was estimated by critical techno-economic judgment [13].

2.2. Methodology adopted for the baseline fleet

The Techno-Economic and Environmental Risk Assessment methodology for the baseline fleet is shown in Fig. 2. The first action is to estimate the initial number of engines in the fleet; this was followed by operating the engines using the available fuel for each year of the project. The performance simulations for all selected engines at design and off-design conditions were done with TURBOMATCH; a tool developed at Cranfield University [15–20].

The fuel consumption of the engine at the design point is available in the public domain; the sum of the fuel consumption for all the units of engines in the fleet (ΣF) is calculated. Let FL be the designation for the fuel consumption for the last unit of engine in the fleet.

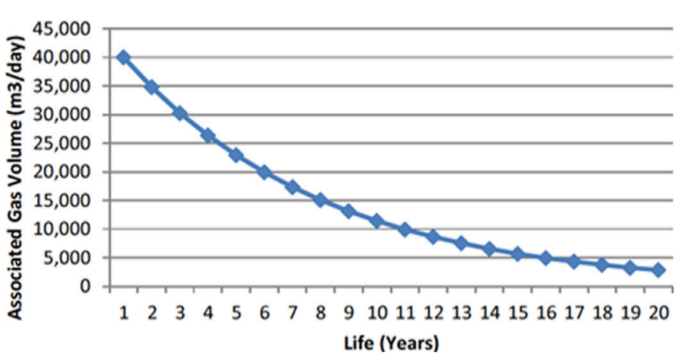


Fig. 1. Associated Gas Decline over 20 Years Period [1].

The fuel available (FA) gradually reduces as the project moves on progressively from one year to the other. As observed in Fig. 2, the following conditions are considered in each year of the project.

- Is $(\sum F - FL) > FA$? (Condition 1)

If a "NO" is the answer to Condition 1, a second condition will be considered;

- Is $(\sum F) \leq FA$ or is $(\sum F) > FA$? (Condition 2)

If $(\sum F) \leq FA$ is true for Condition 2, it means that there is sufficient fuel for all the units of engines in the fleet to run at their design point operating conditions. However, when $(\sum F) > FA$ is true for Condition 2, this means that the fuel available is not enough to meet all the fuel consumption requirements for all the units of engines in the fleet, the last unit of engines in the fleet would have to be operated at a part-load operating condition.

If a "YES" is true for Condition 1, it implies that the fuel available (FA) is no longer enough to meet the fuel consumption requirements of all the units of engines in the fleet even if the last unit of the engines is running at a part-load operating condition, this redundant unit of the engine is divested and the divestment sale is incorporated into the economic assessment for the fleet as seen in Fig. 2.

As illustrated by Fig. 2, after ascertaining the fleet composition; Hephaestus – a Cranfield University FORTRAN-based emission prediction code is used in predicting the emissions from the fleet. This code has been used by various authors for gas turbine emission prediction [16]; [21–23]. The emission results and the emission tax value assumed are used in calculating the annual cost of CO_2 emission from the fleet. The calculated annual cost of emission is incorporated into the economic assessment for the fleet. The power generated by the fleet is sold to the national grid, the revenue obtained is incorporated into the economic assessment of the fleet. The annual operations and maintenance (O & M) cost of the fleet is analyzed from the results gotten from the lifing and maintenance assessment of the fleet. These annual O & M costs are also incorporated into the economic assessment of the fleets, as illustrated in Fig. 2. The economic use of associated gas illustrated in Fig. 2 is repeated yearly for the entire project life. The explanation above describes the model adopted for the baseline fleet. This model yields the maximum power (energy) possible from the fleet and the best divestment time for the redundant units of engines. Consequently, the model also gives the maximum economic return from the project in the form of Net Present Value (NPV). The approach for the baseline is based on critical human techno-economic judgement, not from the optimizer [13].

2.3. Methodology adopted for the optimized fleets

The methodology adopted for the optimized fleets is as shown in Fig. 3. It is very similar to that of the baseline fleet; the only variation is that the fleet composition and the best divestment time for the redundant units of engines are obtained by the optimizer. The optimizer generates the fleet composition that would give the optimum power (energy), the best divestment time for the redundant engines, and the optimum economic return from the project. The influence of degradation on the economic returns of the optimized fleets is also reflected as a major element in this research. The linkage between the Techno-Economic and Environmental Risk Assessment framework and the Genetic Algorithm optimization model is illustrated in Fig. 3. To obtain the fleet composition that generates the maximum power (energy) and optimum economic return (NPV) is the aim of the optimization. The initial fleet of engines and their turbine entry temperatures (TETs) are the design variables for the optimization, while, the annual fuel availability is the constraint for the optimization. Genetic Algorithm in Matlab was used for the optimization

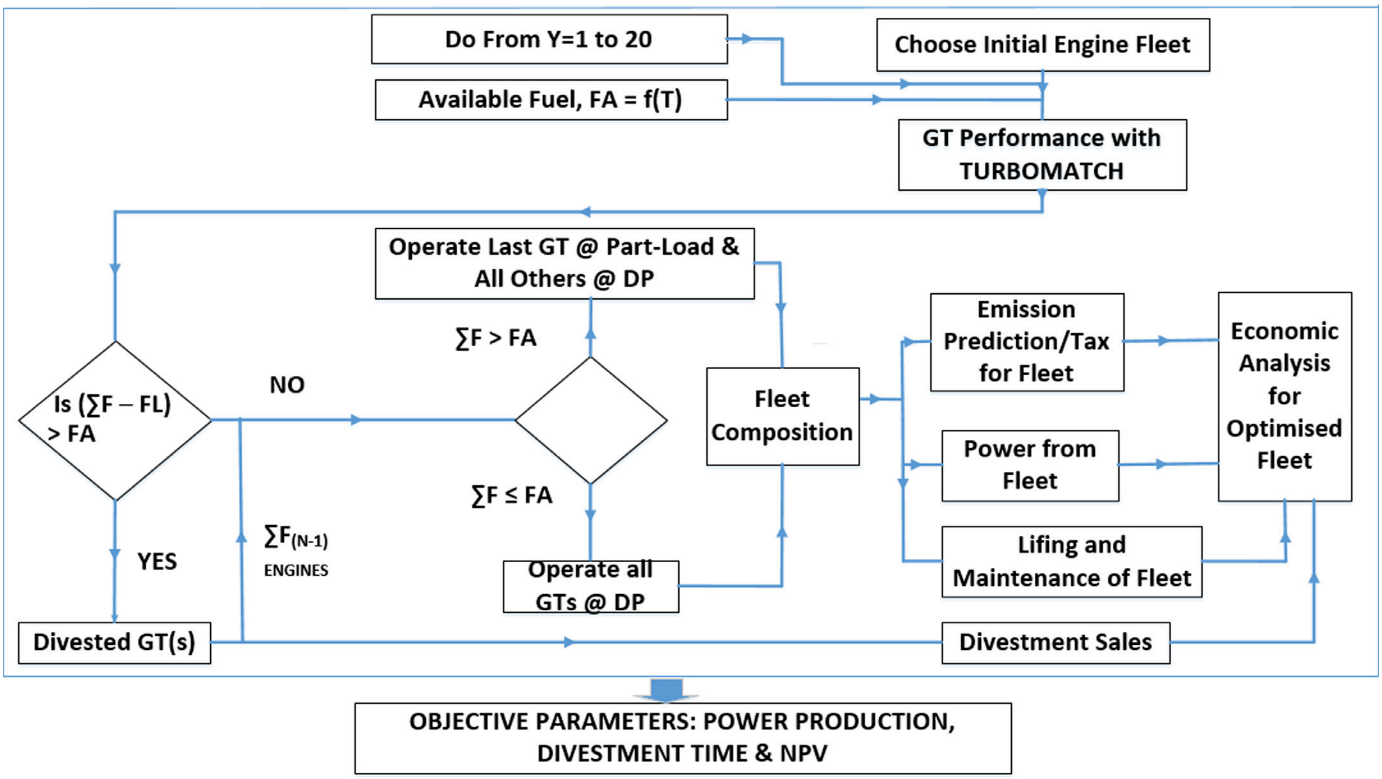


Fig. 2. Techno-Economic and Environmental Risk Assessment Methodology for Associated Gas Utilisation (Baseline) [13].

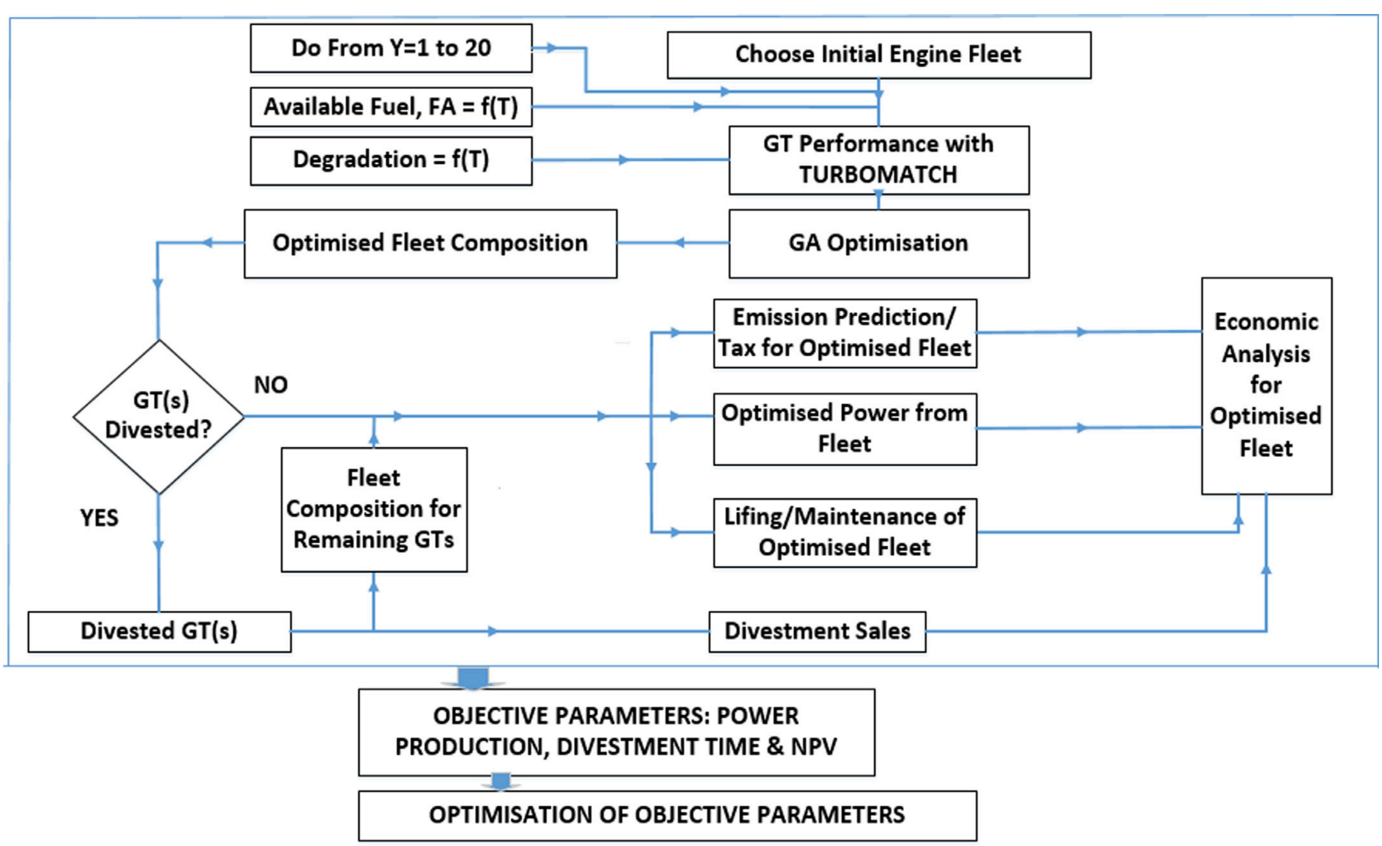


Fig. 3. Techno-Economic and Environmental Risk Assessment Methodology for Associated Gas Utilisation (Optimized) [13].

while the TERA module acted as an external solver. Genetic Algorithm (GA) has been successfully used in optimization. In the field of turbomachinery, Osama Lotfi [24] used GA for the optimization of the aerodynamic shape of a 2-dimensional axial fan cascade. Kikuo et al., [25] found the solution to the planning problem of energy plant configurations by using GA-based optimization.

Oyama et al. used GA to maximize the overall isentropic efficiency and the total pressure ratio of a compressor [26–28]. Ozhan et al. used GA to estimate the optimal aerodynamic performance of a turbine cascade [29–30]. Economic optimization of gas turbine power generation was achieved using GA, Knight et al., [31]; [28, p126].[1]

2.4. The calibration of the genetic algorithm code used

2.4.1. The Genetic algorithm optimization sequence

Fig. 4 shows the sequence followed by the optimizer in achieving the total optimized power, optimized fleet composition, and optimized best divestment time (schedule). The process is repeated for the entire duration of the project (from year 1 to year 20).

2.4.2. Database for the genetic algorithm optimization

Results of the gas turbine performance simulation were used as the database and search domain for the optimizer. The database is made up of four columns, these columns are sets of turbine entry temperatures (TETs) and their corresponding efficiencies, power outputs, and fuel flows. The step size between data points is 5K, 10K, or even more. The optimizer navigates through the search domain for the fleet composition that would give the optimum power production. The optimizer interpolates between steps for data that lie in between the given data set.

2.4.3. The genetic algorithm settings

2.4.3.1. The objective (fitness) function. The objective (fitness) function employed for the optimization in this study is shown in Eq. 1. The Genetic algorithm code used this function in the various iterations of the algorithm to determine the optimum solution.

$$\mathbf{y} = -1 \times [\mathbf{PO}(1) + \mathbf{PO}(2) + \mathbf{PO}(3) + \mathbf{PO}(4) + \mathbf{PO}(5) + \mathbf{PO}(6) + \mathbf{PO}(7) + \mathbf{PO}(8) + \mathbf{PO}(9) + \mathbf{PO}(10) + \mathbf{PO}(11) + \mathbf{PO}(12) + \mathbf{PO}(13) + \mathbf{PO}(14) + \mathbf{PO}(15) + \mathbf{PO}(16) + \mathbf{PO}(17) + \mathbf{PO}(18) +] \mathbf{PO}(19) + \mathbf{PO}(20) + \mathbf{PO}(21) + \mathbf{PO}(22) + \mathbf{PO}(23) + \mathbf{PO}(24) + \mathbf{PO}(25) \tag{1}$$

"PO" is the optimized power output for the various units of engines in the fleet (25units of engines), whereas, "y" is the total optimized power. The optimization aims to maximize "y".

2.4.3.2. The constraints and constraints equation. The annual fuel availability for the project is the constraints considered in the optimization. The optimizer evaluates the optimized power, optimized fleet composition, and best divestment time (schedule) subject to the constraint of annual fuel availability.

Eq. 2 shows the constraint equation used by the optimizer.

$$\mathbf{C} = \mathbf{Fuel\ C}(1) + \mathbf{Fuel\ C}(2) + \mathbf{Fuel\ C}(3) + \mathbf{Fuel}\ (4) + \mathbf{Fuel\ C}(5) + \mathbf{Fuel\ C}(6) + \mathbf{Fuel\ C}(7) + \mathbf{Fuel\ C}(8) + \mathbf{Fuel\ C}(9) + \mathbf{Fuel\ C}(10) + \mathbf{Fuel\ C}(11) + \mathbf{Fuel\ C}(12) + \mathbf{Fuel\ C}(13) + \mathbf{Fuel\ C}(14) + \mathbf{Fuel\ C}(15) + \mathbf{Fuel}\ (16) + \mathbf{Fuel\ C}(17) + \mathbf{Fuel\ C}(18) + \mathbf{Fuel\ C}(19) + \mathbf{Fuel\ C}(20) + \mathbf{Fuel\ C}(21) + \mathbf{Fuel\ C}(22) + \mathbf{Fuel\ C}(23) + \mathbf{Fuel\ C}(24) + \mathbf{Fuel\ C}(25) - 59.3519 \tag{2}$$

The value "59.3519" in Eq. 2 is the fuel availability (kg/s) for the first year of the project. "Fuel C" is the fuel consumption for the various units of engines. For the constraint requirement to be satisfied,

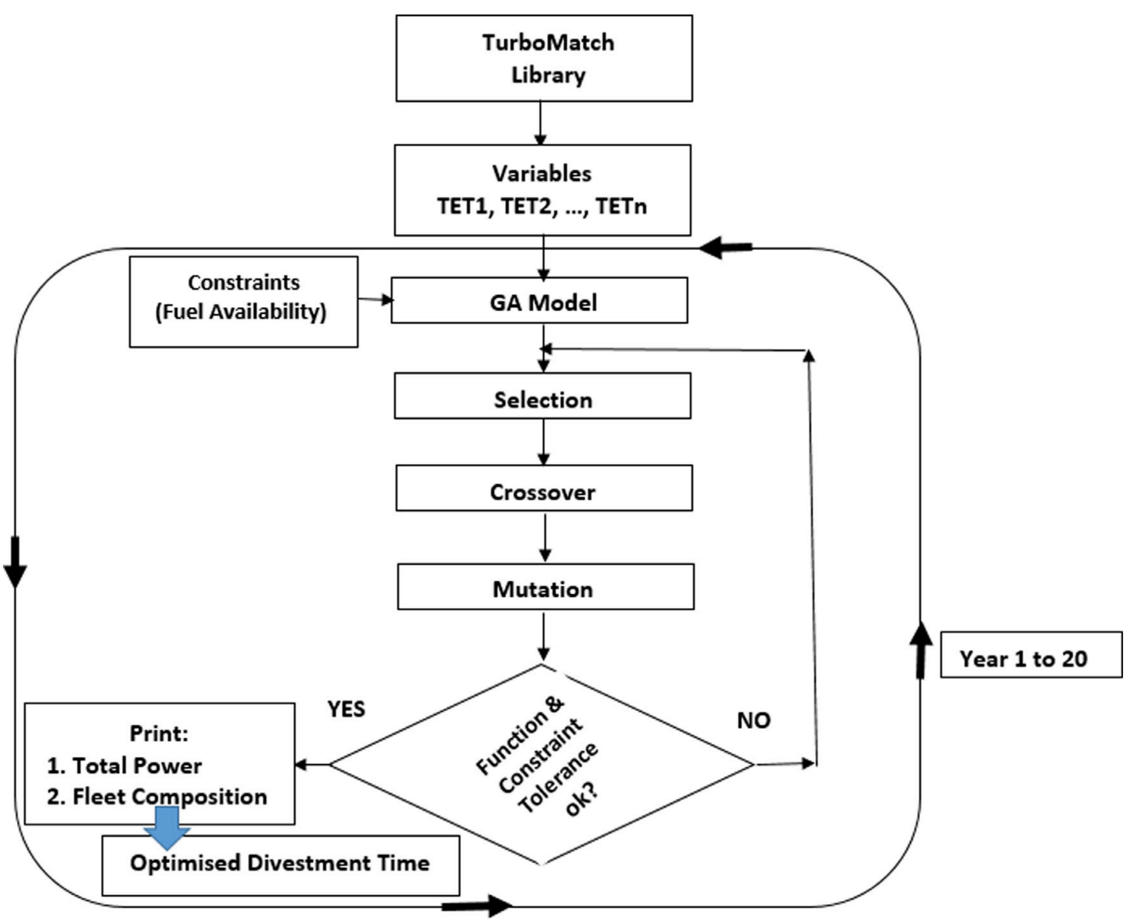


Fig. 4. Genetic algorithm optimization sequence employed [32].

"C" is zero. It should be noted that the constraint equation varies annually depending on the fuel availability for that year.

2.4.3.3. The variables. The variables are the turbine entry temperatures (TETs) of the units of engines in the fleet. The number of units of engines in the fleet determines the number of variables in the optimization. Because the fleet is made up of 25 units of engines, therefore the number of variables is also 25 at the beginning of the optimization. This number reduces with engine divestment.

2.4.3.4. The population size. A population size of 10,000 was mostly used for the optimization. However, lower population sizes were used when the fleet composition became smaller due to engine unit divestment. The quality of the population sizes used was determined by a series of trials.

2.4.3.5. The bounds specified. The optimization bounds were specified using the parameter used as the variables which are the turbine entry temperatures (TET). The design point turbine entry temperature (1550 K) was used as the upper bound while varying values were used at different years as lower bounds.

2.4.3.6. The number of generations and the convergence criteria. The number of generations was initially set at 200, but because the iterations were converging at a much lower number of generations, it was reduced to 50.

The optimization convergence criteria employed in the algorithm are 'FunctionTolerance' and 'ConstraintTolerance'. By default, the Genetic algorithm uses 1.0e−06 for both criteria. This value was used at the beginning of the optimization, however, for better accuracy; 1.0e−09 was later used in most cases. These tolerances are limits that help in getting the optimal solution.

3. Results and discussion

3.1. Design point performance data

Table 2 shows the performance data for the real engine and the engine model (AD43 Engine). The performance simulation was done using TURBOMATCH software.

3.2. Optimization results validation procedure

To validate the results gotten from the Genetic algorithm optimizer, baseline analysis was done for the power produced (MW) by the units of engines in the baseline fleet. The power produced by the baseline fleet was then compared with that produced by the optimized fleet (clean).

3.2.1. Baseline fleet composition

The fleet composition that would probably yield the maximum power (energy) and optimum economic return, which is based on a critical human techno-economic judgement is termed as the baseline fleet composition. This fleet composition is shown in Table 3. Shown in the table is the number of units of engines that were operated at their design point, the number operated at part-load operating conditions, and their corresponding Turbine Entry Temperatures (TETs) for the whole life span of the project.

Table 2
Performance parameters for the Real Engineand Engine Model.

Parameters	Real data	Engine model
Exhaust mass flow [Kg/s]	127.0	131.9
Turbine Entry Temperature, TET [K]	Not available	1550
Shaft power [MW]	43.4	43.3
Thermal efficiency [%]	41	40
Overall pressure ratio	29.1	29.1
Fuel flow [Kg/s]	Not available	2.3958

Source of data for the Real Engine [33]

Table 3
Baseline Fleet Composition

Year	Number of AD43 engines running at design point TET [1550K]	Part-load TET [K]
1	24	1416.5
2	21	1354.1
3	18	1405.5
4	16	-
5	14	-
6	12	-
7	10	1401.2
8	9	-
9	8	-
10	7	-
11	6	-
12	5	-
13	4	1369
14	4	-
15	3	1352
16	3	-
17	2	1371.7
18	2	-
19	2	-
20	1	1408.5

3.2.2. Optimised fleet compositions for all fleets

The optimized fleet composition gives the maximum power (energy) and optimum economic return (NPV) from the fleet. Fig. 5 shows the optimized fleet compositions for the pessimistic degraded fleet. Included in the figure are the number of units of engines in operation and their respective operational turbine entry temperatures (TET). The figure also gives an idea of the number of redundant units of engines that have been divested, which is represented with empty spaces.

3.3. Validation of the optimization model and results

To validate the accuracy of the optimization model and its results; the optimized power produced by the optimized clean fleet is compared to that of the baseline fleet. All the scenarios considered in the study are all subject to the same constraint of annual fuel availability.

3.3.1. Comparison of the optimized power/energy production by the optimized (clean fleet) and baseline fleet

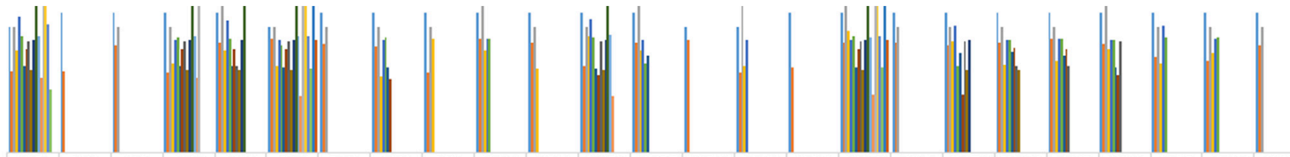
Fig. 6 shows the difference in percentage between the optimized power production for the optimized clean fleet and that of the baseline fleet.

Fig. 7 shows the power production for the optimized and baseline fleets on an annual basis. The results seen in Figs. 6 and 7 show that the optimization model and its results are reliable, this is because the optimizer yielded results that are better than that of the baseline in most of the years of the project.

3.4. Optimized best divestment time and the effect of degradation on the divestment time of redundant units of engines in the fleets

To invest in the economic utilization of associated gas for power generation using gas turbines; a model would be required to evaluate

[1] GA (genetic algorithm), TERA (techno-economic and environmental risk assessment), GT(s) (gas turbines), DP (design point), FA (fuel available), ΣF (sum of fuel consumption for the engines), Y (year), FL (fuel requirement for the last unit of engine), f (T) (function of time), $\Sigma F_{(N-1)\ \mathrm{ENGINES}}$ (Sum of Fuel Requirements for the Undivested Engines), NPV (net present value)



PROJECT TIME [YRS]	GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	1534	1546	1546	1546	1546	1535	1546	1546	1546	1546	1546	1546	1546	1534	1534	1546	1546	1546	1546	1546	1546	1546	1546	1546	1546
YR2	1501	1502	1521	1501	1523	1526	1522	1520	1500	1526	1522	1505	1523	1525	1500	1504	1523	1523	1521	1523	1526	1522	1512	1509	1521
YR3	1535		1534	1534	1550	1534	1535	1534	1534	1550	1534	1534	1550		1550		1550	1534	1534	1534	1534	1550	1534	1534	1534
YR4	1517			1507	1517	1505		1498	1525	1517	1503	1527	1517		1505		1532		1524	1506	1509	1518	1507	1515	
YR5	1542			1525	1539	1525		1525		1526		1540	1525		1525		1525		1536	1525	1525	1525	1535	1526	
YR6	1527			1527	1525	1521		1526		1526		1527	1507				1527		1505	1525	1526	1525	1527	1527	
YR7	1505			1505	1506	1504		1504				1503	1513				1505		1515	1516	1513	1504			
YR8	1518			1518	1518	1518		1495				1498					1518		1484	1518	1518	1498			
YR9	1524			1524	1505	1524						1524					1524		1524	1505	1505	1524			
YR10	1502			1502	1502	1502						1502					1502		1502	1502					
YR11	1525			1525	1525	1525						1525					1525		1525						
YR12	1550			1550	1550	1550						1550					1550								
YR13	1528			1528		1528						1528					1527								
YR14	1497			1497		1483						1483					1483								
YR15	1550			1550		1550											1550								
YR16	1550					1550											1550								
YR17	1537					1528											1528								
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YR19						1550											1550								
YR20						1525											1525								

ANNUAL NUMBER OF AD43 UNITS IN THE FLEET & THEIR TETs [K]

Fig. 5. Optimized Fleet Composition for the Pessimistic Degraded Fleet.

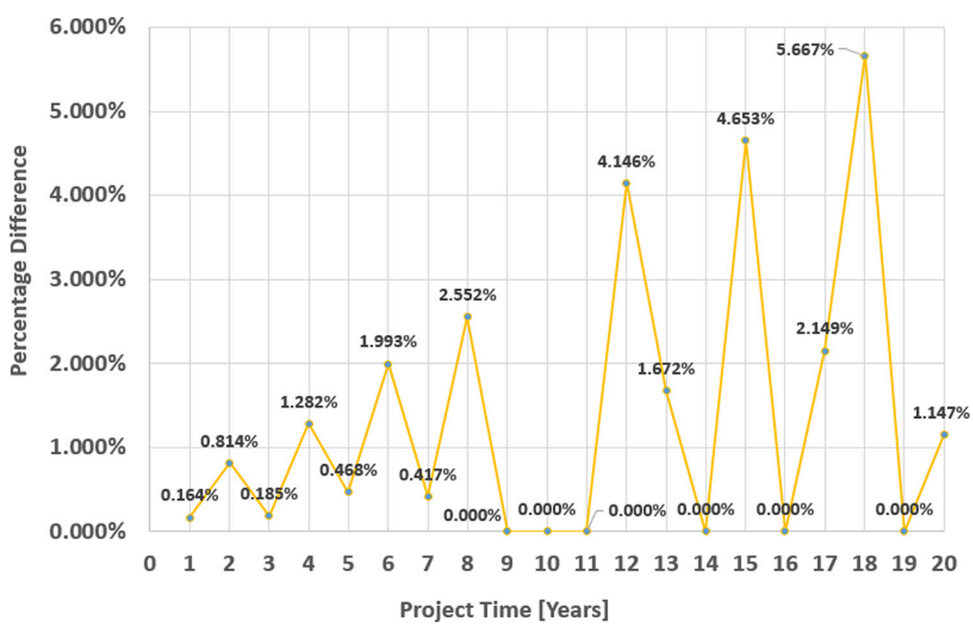

Fig. 6. Percentage Difference in Power Production by the Optimized (Clean) Fleet and the Baseline Fleet.

the best divestment time for the redundant unit (s) of engines. This model would also evaluate the effect of gas turbine degradation on the divestment time.

Fig. 8 shows the optimized best divestment time and the effect of gas turbine degradation on the divestment time of redundant units of engines in different fleets. As expected, results show that engine degradation extends the divestment time. As an example, considering the 2nd year of the project; 3, 3, 2, 1, 0 are the respective number of units of engines divested in the baseline, clean (optimized), optimistic degraded, medium degraded, and pessimistic degraded fleets.

3.5. *Percentage reduction in average optimized efficiency of fleets*

Fig. 9 shows the annual percentage reductions in average optimized efficiencies for the optimistic, medium, and pessimistic fleets in comparison with the average optimized efficiency of the optimized (clean) fleet. Degradation in the compressor of the various units of engines had a significant effect on the efficiencies of the engines, and consequently on the average optimized efficiencies. As can be seen in Fig. 9, on an annual basis, the pessimistic degraded fleet has the highest percentage reduction in average optimized efficiency, whereas the optimistic has the least.

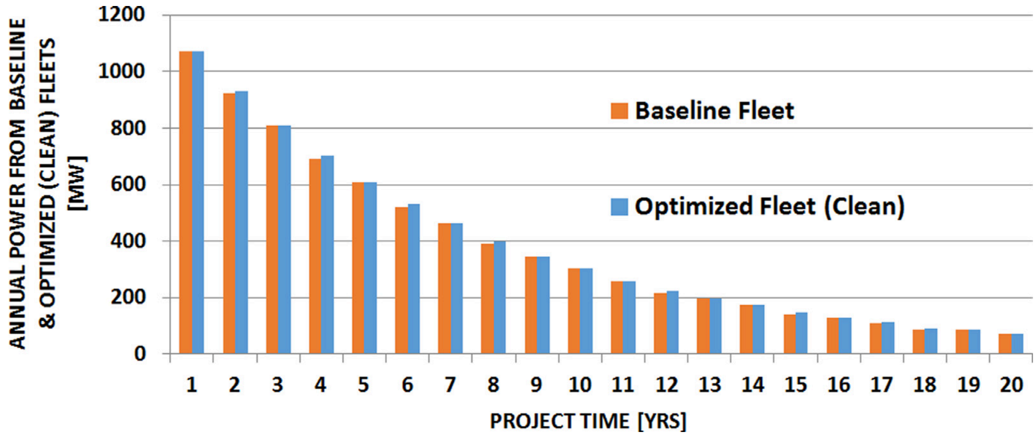

Fig. 7. Annual Power Production Values for the Baseline and Optimised Fleets.

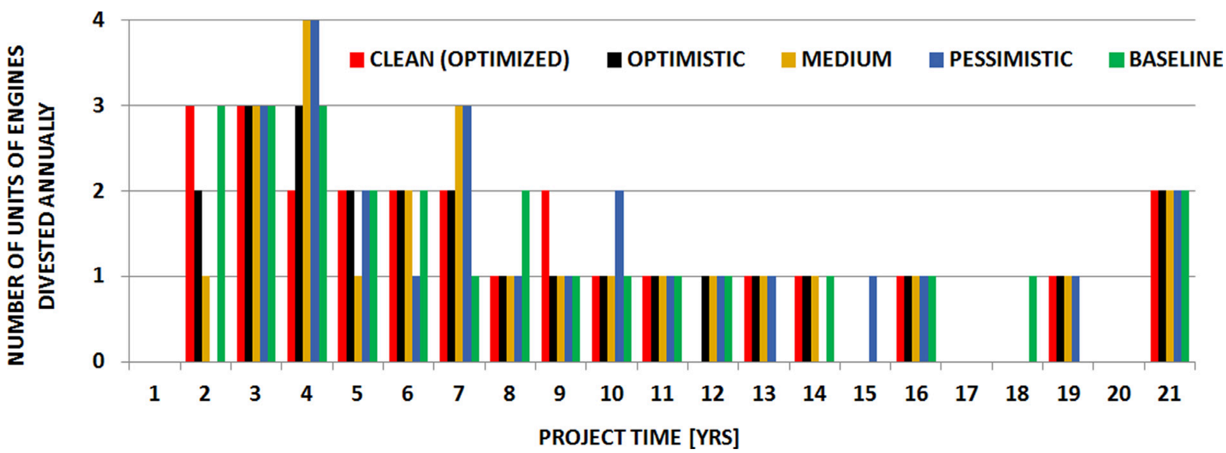

Fig. 8. Optimized Engine Units' Best Divestment Time & the Effect of Gas Turbine Degradation on Divestment Time.

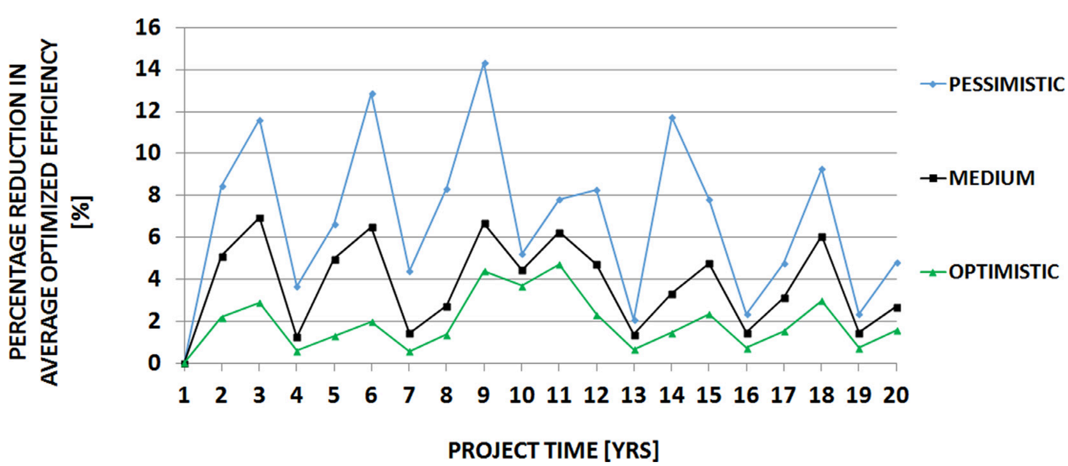

Fig. 9. Percentage reduction in average optimized efficiencies on an annual basis.

3.6. Total revenue generated from sold electricity

Fig. 10 shows the total revenue generated from the sold electricity for all the fleets in this research.

As can be seen, 8.92 billion dollars is the highest revenue generated, whereas 8.31 billion dollars is the least generated, and these are for the optimized fleet (clean) and pessimistic degraded fleet respectively. Degradation reduced the total revenue of the project by 1.6%, 3.8%, and 6.8% for the optimistic, medium, and pessimistic fleets respectively.

3.7. Total operations and maintenance cost for all fleets

Shown in Fig. 11 is the total operations and maintenance costs for all the fleets. As expected, the higher degraded fleets have higher operations and maintenance costs. As can be seen from Fig. 11, the pessimistic degraded fleet has the highest total operations and maintenance cost of 1.35 billion and the optimized fleet (clean) has the least with a value of 1.31 billion. Degradation increased the operations and maintenance cost of the project by 0.7%, 1.9%, and 2.8% for the optimistic, medium, and pessimistic fleets respectively.

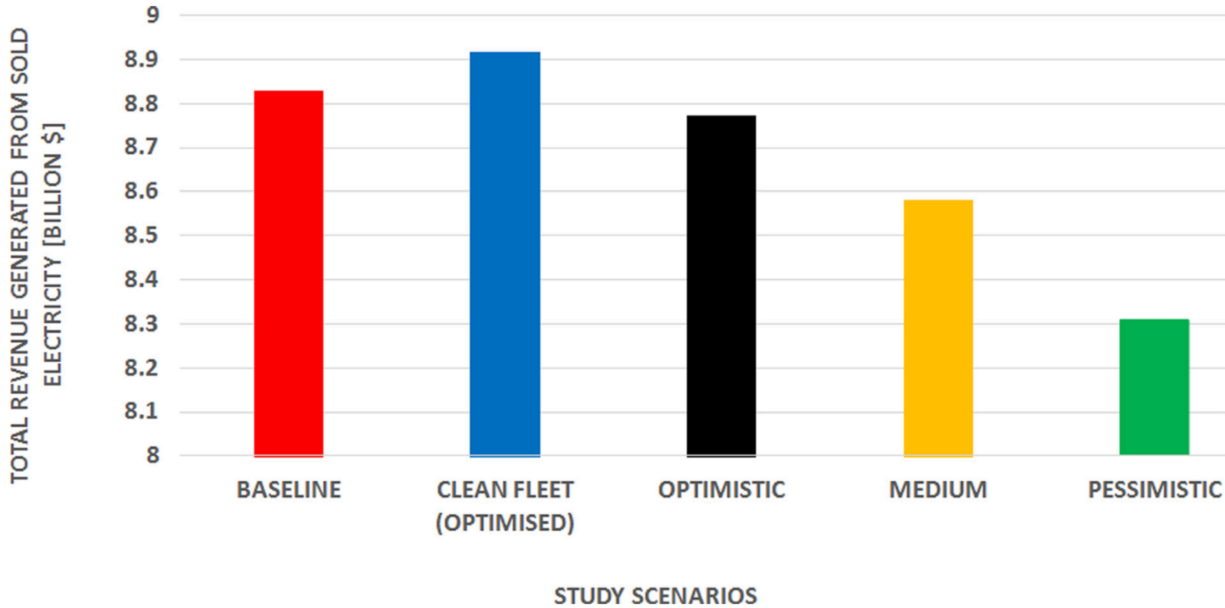

Fig. 10. Total Revenue Generated from Sold Electricity.

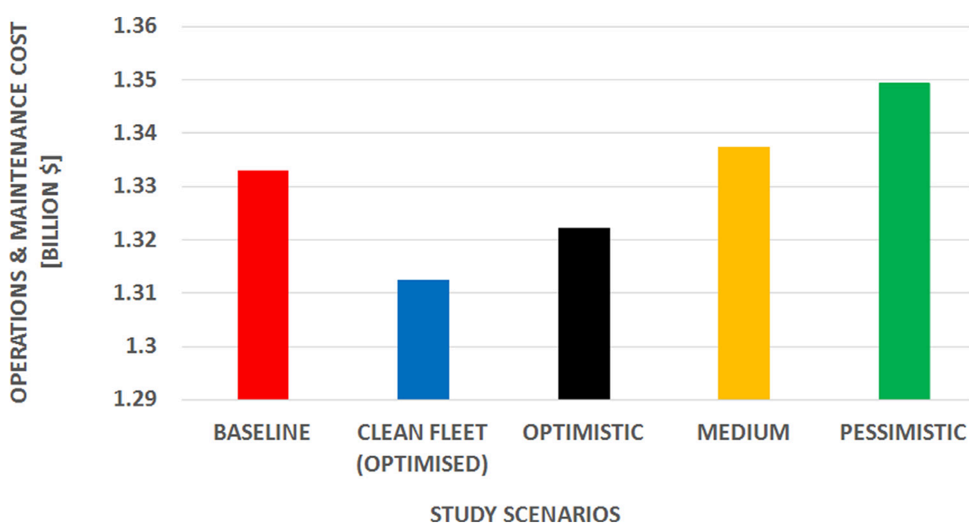

Fig. 11. Total Operations and Maintenance Costs for all Fleets.

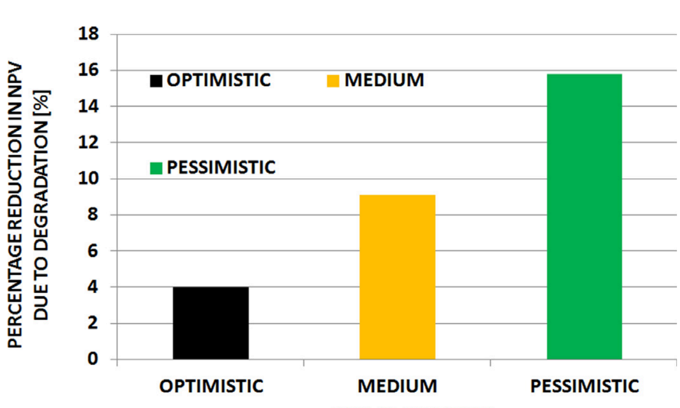

Fig. 12. Assessment of the Impact of Degradation on the Economic Use of Association Gas.

3.8. Optimised economic return (NPV) and the impact of degradation on the economic use of associated gas

The robust model developed and adopted for the economic utilization of associated gas incorporated various techno-economic factors.

The combined effect of varying techno-economic factors such as capital investment, emission tax, operations, and maintenance cost, gas turbine divestment sales, staff salaries, revenue from sold electricity, and loan repayment was incorporated into the model to get the economic return. Results show that 2.39, 2.58, 2.73, 2.79, and $2.84 b are the economic return from the pessimistic, medium, optimistic, baseline, and clean (optimized) fleets respectively. As can be seen from Fig. 12, degradation reduced the NPV of the project by 15.8%, 9.1%, and 4.0% for the pessimistic, medium, and optimistic degraded fleets respectively.

It should be noted that the contents of this paper are extracts from a research work carried out by the author [32].

4. Conclusion

A high volume of associated gas is being wasted to flaring in some parts of the world. The Techno-Economic and Environmental Risk Assessment (TERA) framework was adopted for a broad and multi-dimensional optimization of the economic return of fleets of gas turbines utilizing flared associated gas. Fleets made up of units of a 43.3 MW aero-derivative engine were considered.

An increase of 1.0% and 1.6% respectively in the energy and NPV of the optimized clean fleet as against the baseline were achieved. The economic performance of the fleets shows the optimized fleet (clean) having the highest NPV of $2.84 b and the pessimistic degraded fleet having the least NPV of $2.39b. Degradation reduced the NPV of the project by 4.0%, 9.1%, and 15.8% for the optimistic, medium, and pessimistic degraded fleets.

Presented in this paper is a methodology that would be used for the economic utilization of associated gas. The novelty of this paper is seen in the detailed evaluation of the effect of engine degradation on the optimized divestment schedule of redundant engines in a fleet. Also, the effect of the divestment of the redundant engines on the optimized power, optimized efficiencies, operations and maintenance costs, and on the revenue generated from sold electricity have all been assessed, these are missing in the public domain. Instead of flaring associated gas, this methodology could be employed by Governments and Investors for associated gas investment planning and decision making. Employing this methodology in the economic utilization of associated gas using gas turbines would not only yield huge energy and economic benefits, but it would also greatly reduce associated gas flaring, environmental deterioration, and pollution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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